The Gamma Factory

PBC workshop, CERN, June 2018

Reyes Alemany-Fernandez, CERN
representing the Gamma Factory study group

Gamma Factory group members

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Outline

1. Gamma Factory & fundamental and applied physics highlights

2. 2017 Xe+39 MDs results
3. Plans for the 2018 MDs with PB+54, Pb+80 and PB+81
4. Preliminary results of the SPS MD 06.06.2018

5. GF software development

6. Towards the PoP experiment in the SPS

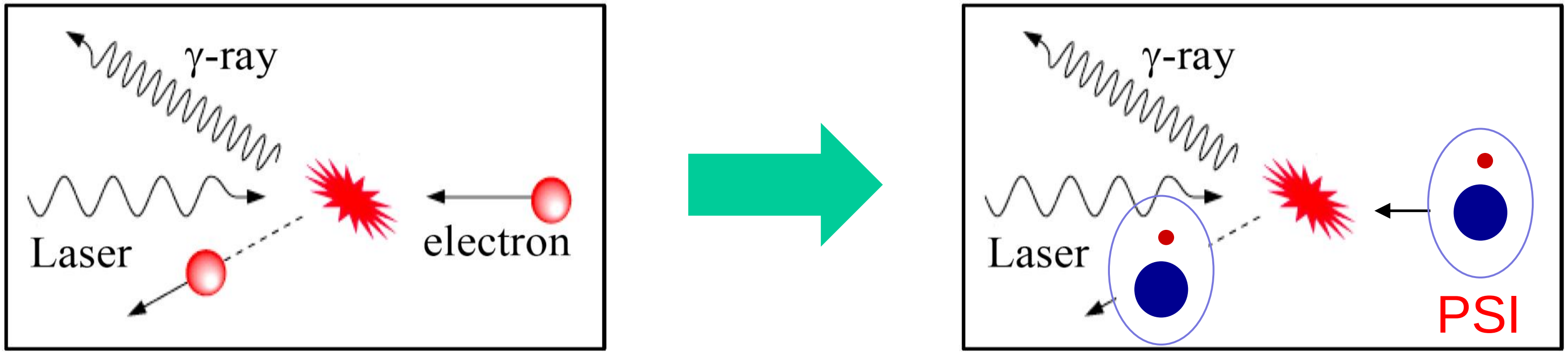
7. Impact/synergy of the GF activities on the on-going and future CERN research programme:
    - AWAKE
    - HL-LHC with iso-scalar beams
    - GF and the CERN muon collider studies (ARIES workshop, July 2018)

9. The way forward

What is Gamma Factory?

Gamma-ray beam – the backbone of Gamma Factory

The idea: replace an electron beam (used in the existing gamma sources) by a beam of Partially Stripped Ions **(PSI)**



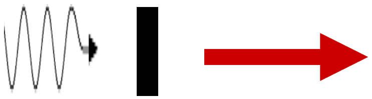
- **up to 7 orders of magnitude increase of gamma fluxes**
- **gamma rays of up to 400 MeV (for 7 TeV PSI @LHC)**

Beams and collision schemes

primary beams:

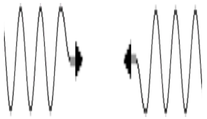
- partially stripped ions
- electron beam (for LHC)
- gamma rays

secondary beam sources:



- polarised electrons,
- polarised positrons
- polarised muons
- neutrinos
- neutrons
- vector mesons
- radioactive nuclei

collider schemes:



$\gamma-\gamma$ collisions,

E_{CM} = 0.1 – 800 MeV

$\gamma-\gamma_L$ collisions,

E_{CM} = 1 – 100 keV

$\gamma-p(A)$, ep(A) collisions,

E_{CM} = 4 – 200 GeV

Using the EXISTING

world unique opportunities

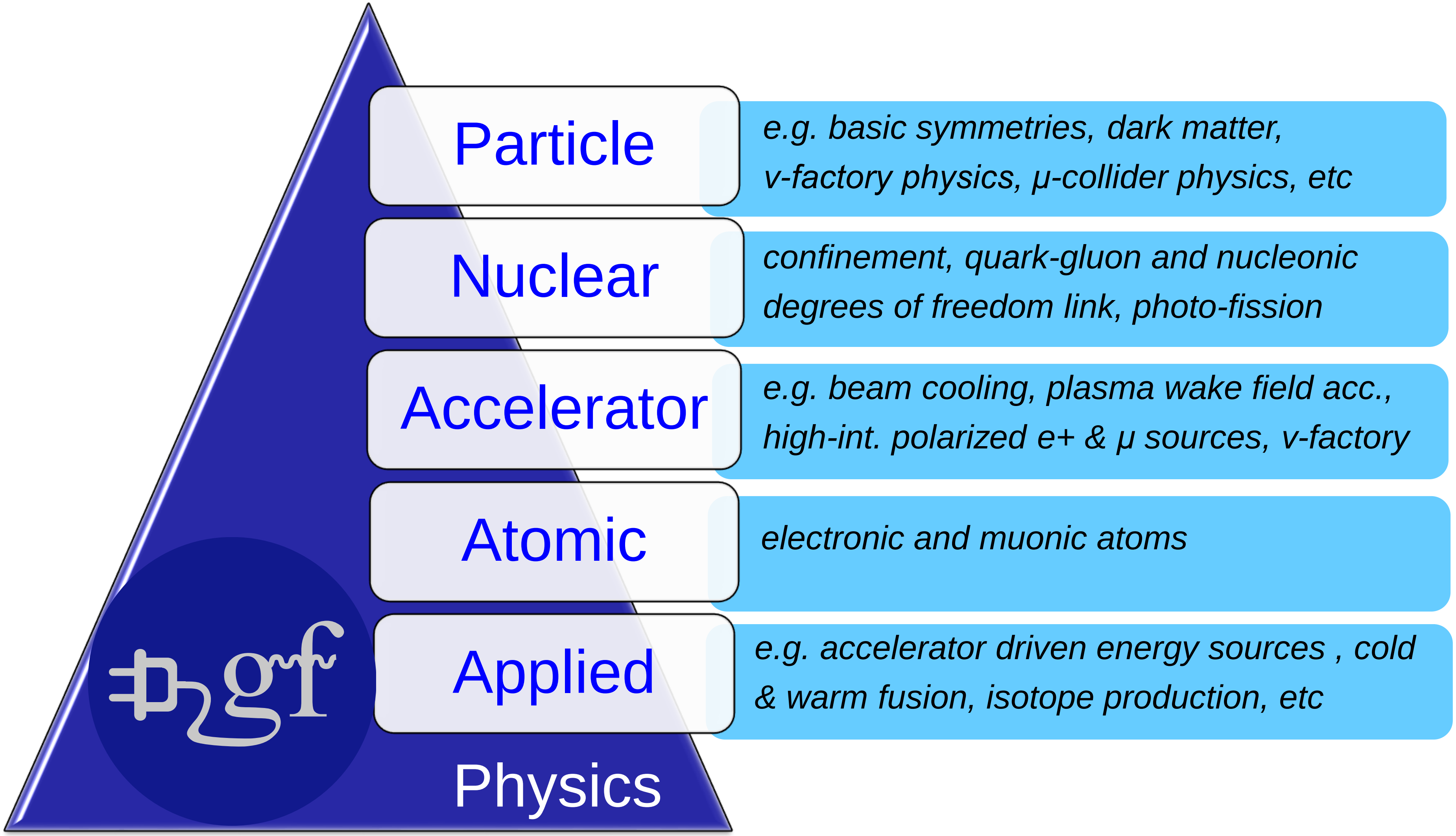
offered by the

CERN accelerator complex

and scientific infrastructure

Basic and applied physics highlights

GF research highlights

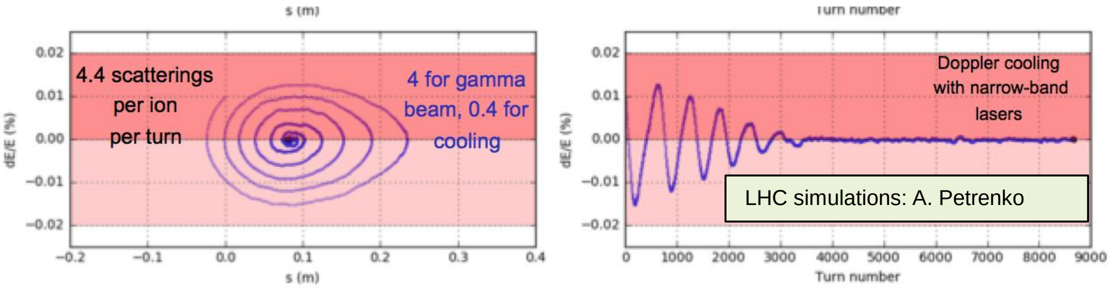


Particle	*e.g. basic symmetries, dark matter, v-factory physics, μ-collider physics, etc*
Nuclear	*confinement, quark-gluon and nucleonic degrees of freedom link, photo-fission*
Accelerator	*e.g. beam cooling, plasma wake field acc., high-int. polarized e+ & μ sources, v-factory*
Atomic	*electronic and muonic atoms*
Applied	*e.g. accelerator driven energy sources , cold & warm fusion, isotope production, etc*

Physics

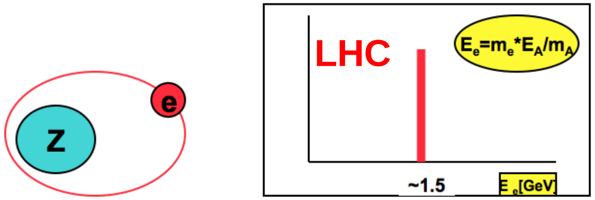
Potential impact of the Gamma Factory R&D on the on-going CERN programme (examples)

- *Doppler beam cooling technology*

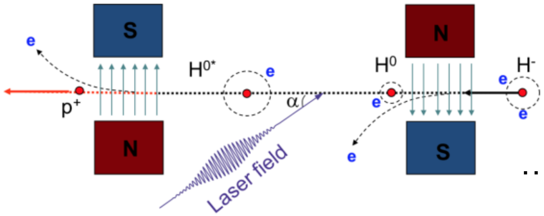


LHC simulations: A. Petrenko

- *"No cost", monochromatic electron beam (energies up to 1.5 GeV)*



- *"Elegant" H^- injection scheme to circular machines (protons undisturbed)*

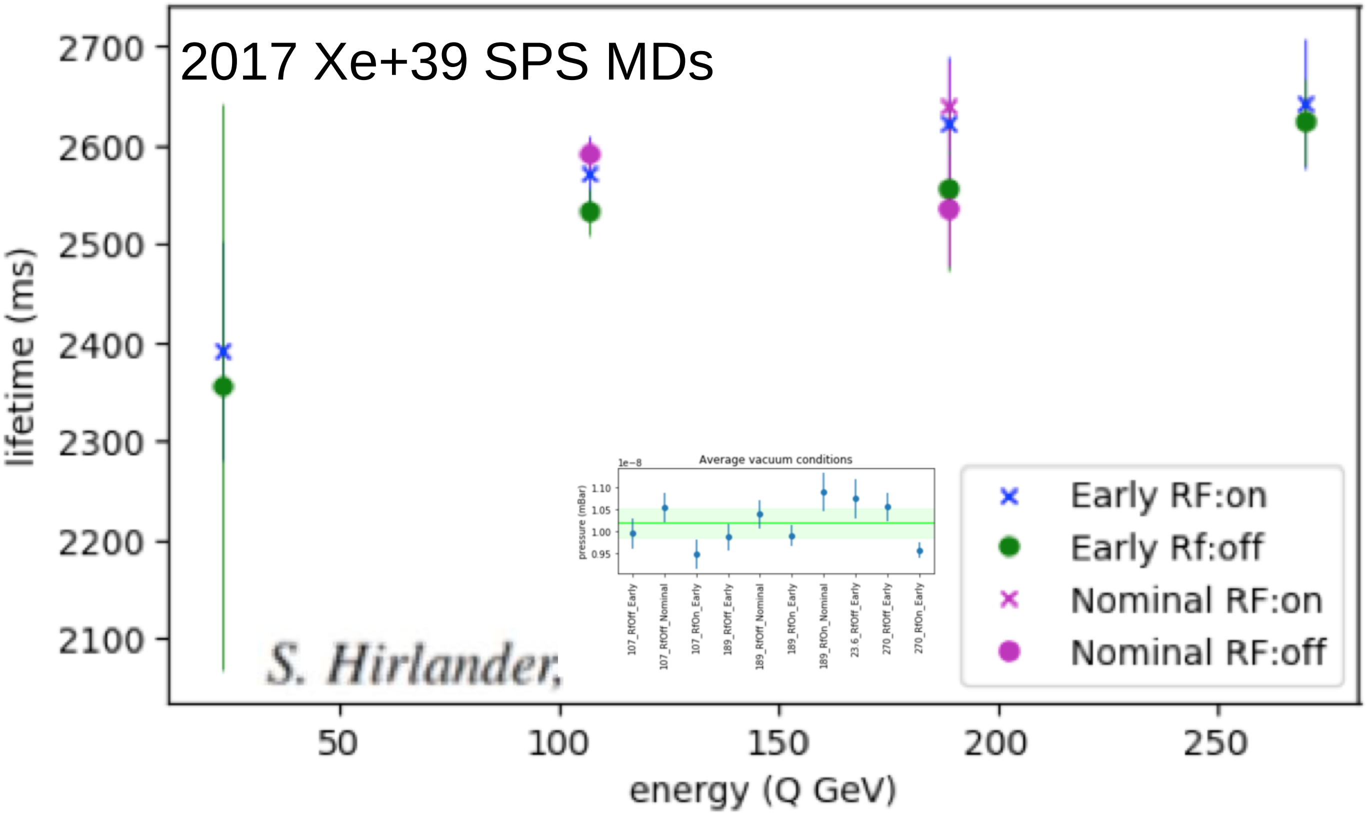


…recent progress at Oak Ridge

Results of the 2017 Xe+39 MDs and their role in preparation of the 2018 MDs

What we have already learned from the 2017 Xe+39 SPS MDs ?

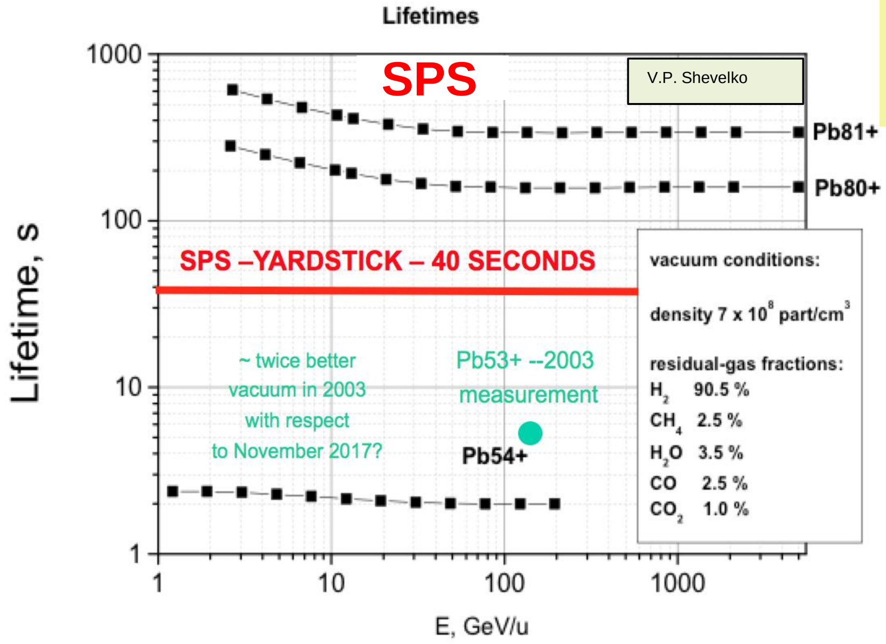
Xe+39 beam life time, as expected, is driven predominantly by the losses of ions due to electron stripping by the rest gas molecules.



What we have already learned from the 2017 Xe+39 runs in the SPS?

The 2017 SPS measurements allowed us to:

1. Constrain the vacuum quality and the rest gas molecular content.
2. Cross-check the simulations used in the extrapolations to other ions species and LHC energies.



3. Calculate the expected Pb+80 and Pb+81 beam life time, for the vacuum conditions of the 2017 Xe+39 runs, which exceeds comfortably the SPS injection + ramping time!
4. Significantly better vacuum in the LHC – lifetime rise by a factor of 100, w.r.t SPS expected (if dominated by the electron stripping in beam-gas collisions)!

Plans for the 2018 MDs

2018 SPS and LHC MDs – strategy

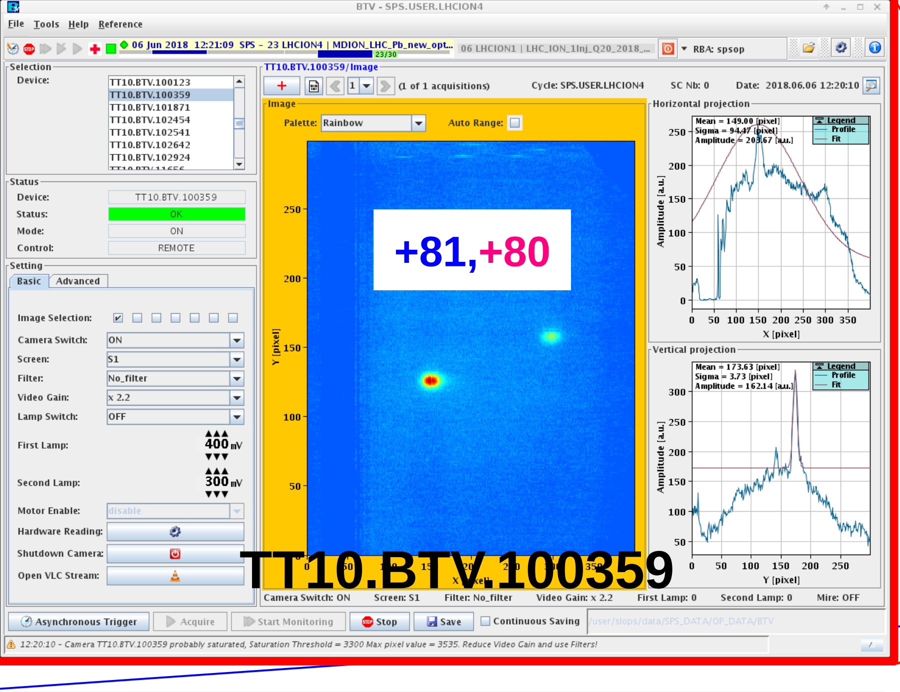
SPS

- Calibrate the 2018 vacuum with the initial PB+54 runs.
- Studies of Pb+54 → Pb+80 and Pb+54 → Pb+81 stripping efficiencies.
- SPS test of the relative importance of multi-electron and single electron losses.
- Measurement of the strength of the intra-beam-stripping processes (intensity and energy dependence of the beam life-time).
- Realistic extrapolation of the beam life-time to the LHC case (following an experimental verification of all the modelling assumption).
- Pb+80 versus Pb+81 choice for the LHC runs.

LHC

- Start with the life time measurement of a single bunch at the injection energy and at the top energy, loss maps, vacuum quality evolution, beam emittance evolution.
- Vary bunch intensity.
- Study the dynamical vacuum and BLM signals as a function of the number of bunches.

First results of the 2018 MDs



06 Jun 2018 12:21:09 SPS - 23 LHCION4 | MDION_LHC_Pb_new_opt... 23/30 06 LHCION1 | LHC_ION_1Inj_Q20_2018_... RBA: spsop

TT10.BTV.100359/Image (1 of 1 acquisitions) Cycle: SPS.USER.LHCION4 SC Nb: 0 Date: 2018.06.06 12:20:10

Device: TT10.BTV.100123
TT10.BTV.100359
TT10.BTV.101871
TT10.BTV.102454
TT10.BTV.102541
TT10.BTV.102642
TT10.BTV.102924

Device: TT10.BTV.100359
Status: OK
Mode: ON
Control: REMOTE

Camera Switch: ON
Screen: S1
Filter: No_filter
Video Gain: x 2.2
Lamp Switch: OFF
First Lamp: 400 mV
Second Lamp: 300 mV
Motor Enable: disable
Palette: Rainbow
Auto Range: ☐

Horizontal projection: Mean = 149.00 [pixel] Sigma = 94.47 [pixel] Amplitude = 203.67 [a.u.]

Vertical projection: Mean = 173.63 [pixel] Sigma = 3.73 [pixel] Amplitude = 162.14 [a.u.]

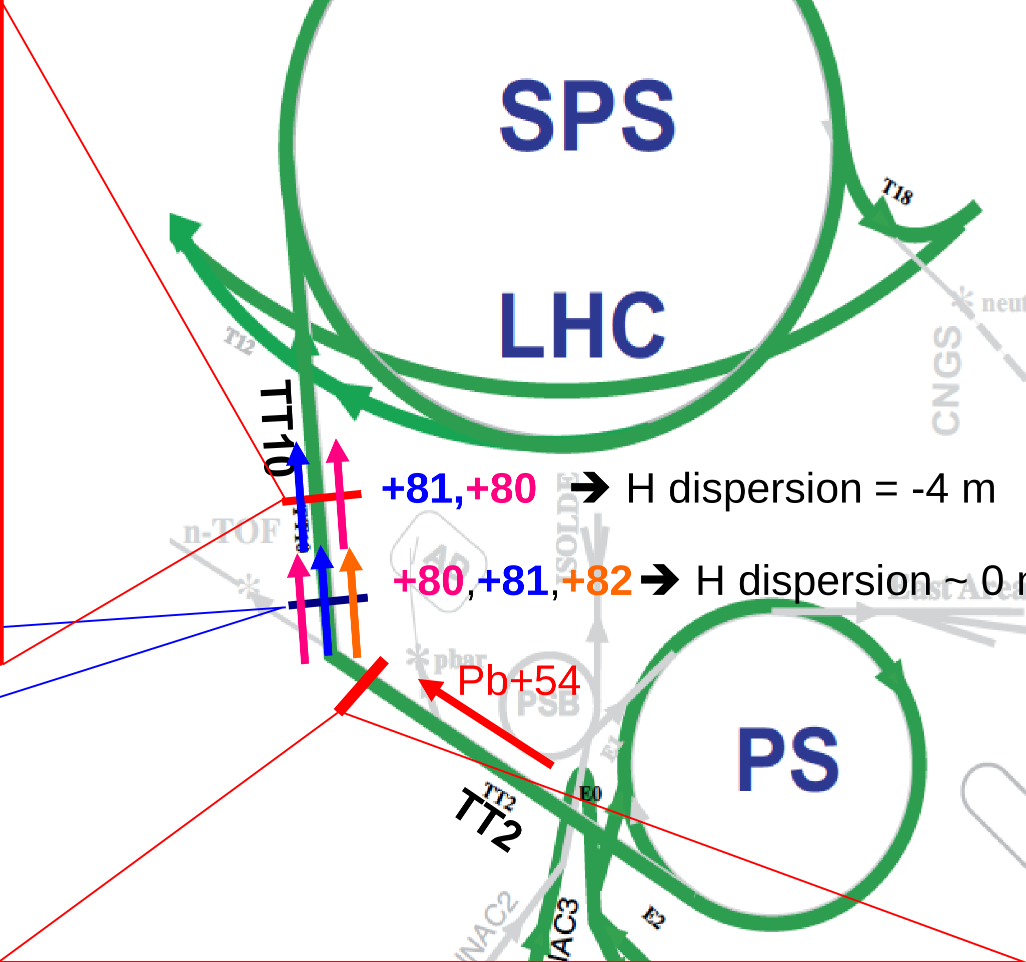
Camera Switch: ON Screen: S1 Filter: No_filter Video Gain: x 2.2 First Lamp: 0 Second Lamp: 0 Mire: OFF

/user/slops/data/SPS_DATA/OP_DATA/BTV

12:20:10 - Camera TT10.BTV.100359 probably saturated, Saturation Threshold = 3300 Max pixel value = 3535. Reduce Video Gain and use Filters!

+81,+80

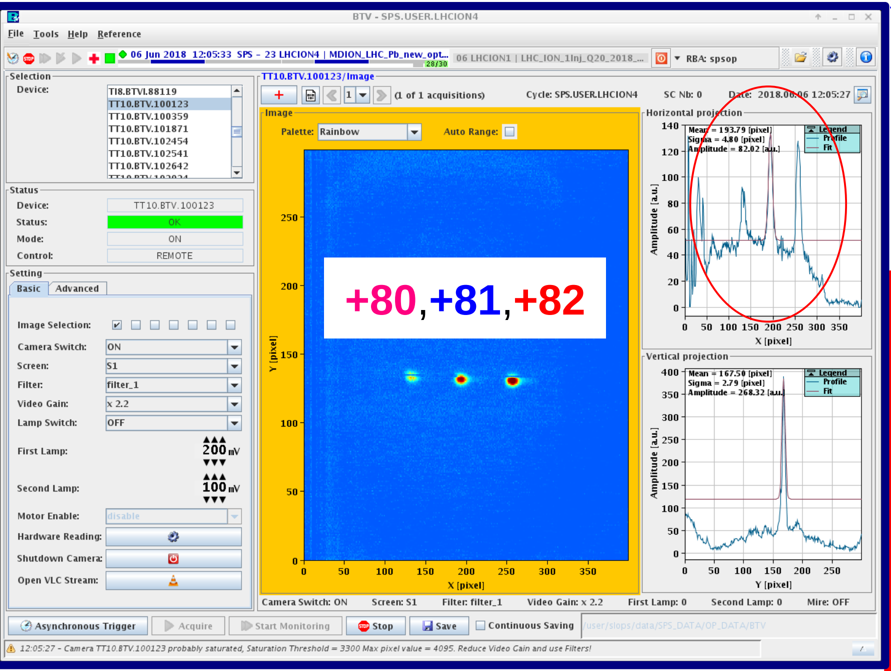
TT10.BTV.100359



+81,+80 ➔ H dispersion = -4 m

+80,+81,+82 ➔ H dispersion ~ 0 m

Pb+54



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TT10.BTV.100359
TT10.BTV.101871
TT10.BTV.102454
TT10.BTV.102541
TT10.BTV.102642

Device: TT10.BTV.100123
Status: OK
Mode: ON
Control: REMOTE

Camera Switch: ON
Screen: S1
Filter: filter_1
Video Gain: x 2.2
Lamp Switch: OFF
First Lamp: 200 mV
Second Lamp: 100 mV
Motor Enable: disable
Palette: Rainbow
Auto Range: ☐

Horizontal projection: Mean = 193.79 [pixel] Sigma = 4.80 [pixel] Amplitude = 82.02 [a.u.]

Vertical projection: Mean = 167.50 [pixel] Sigma = 2.79 [pixel] Amplitude = 268.32 [a.u.]

Camera Switch: ON Screen: S1 Filter: filter_1 Video Gain: x 2.2 First Lamp: 0 Second Lamp: 0 Mire: OFF

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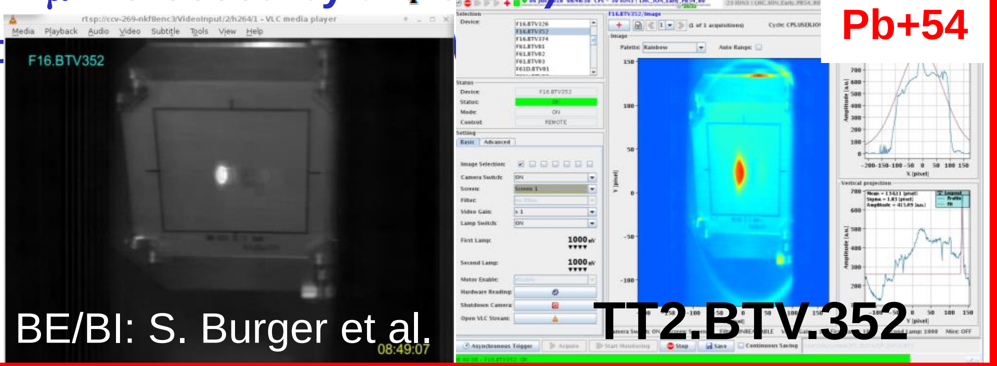
12:05:27 - Camera TT10.BTV.100123 probably saturated, Saturation Threshold = 3300 Max pixel value = 4095. Reduce Video Gain and use Filters!

+80,+81,+82

TT10.BTV.100123

Stripper: 150µm (45° inclined ➔ 212µm crossed by the beam) thick Al fo

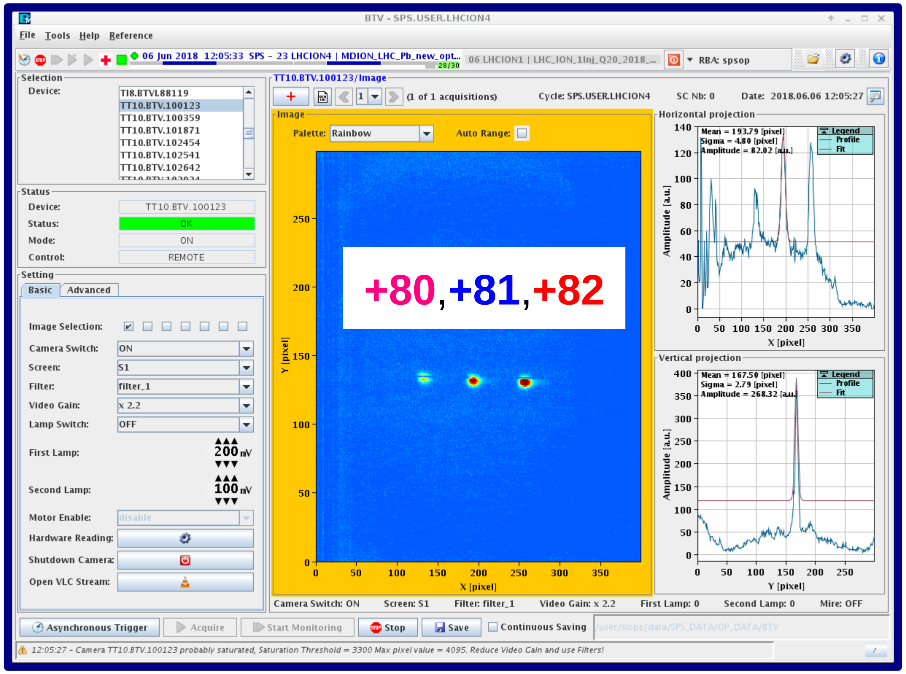


Pb+54

BE/BI: S. Burger et al.

TT2.BTV.352

June 2018 MDs - first results



06 Jun 2018 12:05:33 SPS - 23 LHCION4 | MDION_LHC_Pb_new_opt... 28/30

06 LHCION1 | LHC_ION_1Inj_Q20_2018_...

RBA: spsop

Device: TI8.BTVI.88119, TT10.BTV.100123, TT10.BTV.100359, TT10.BTV.101871, TT10.BTV.102454, TT10.BTV.102541, TT10.BTV.102642

TT10.BTV.100123/Image

(1 of 1 acquisitions)   Cycle: SPS.USER.LHCION4   SC Nb: 0   Date: 2018.06.06 12:05:27

Device: TT10.BTV.100123
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Mode: ON
Control: REMOTE

Image Selection: ☑ ☐ ☐ ☐ ☐ ☐ ☐
Camera Switch: ON
Screen: S1
Filter: filter_1
Video Gain: x 2.2
Lamp Switch: OFF
First Lamp: 200 mV
Second Lamp: 100 mV
Motor Enable: disable
Hardware Reading:
Shutdown Camera:
Open VLC Stream:

Palette: Rainbow   Auto Range: ☐

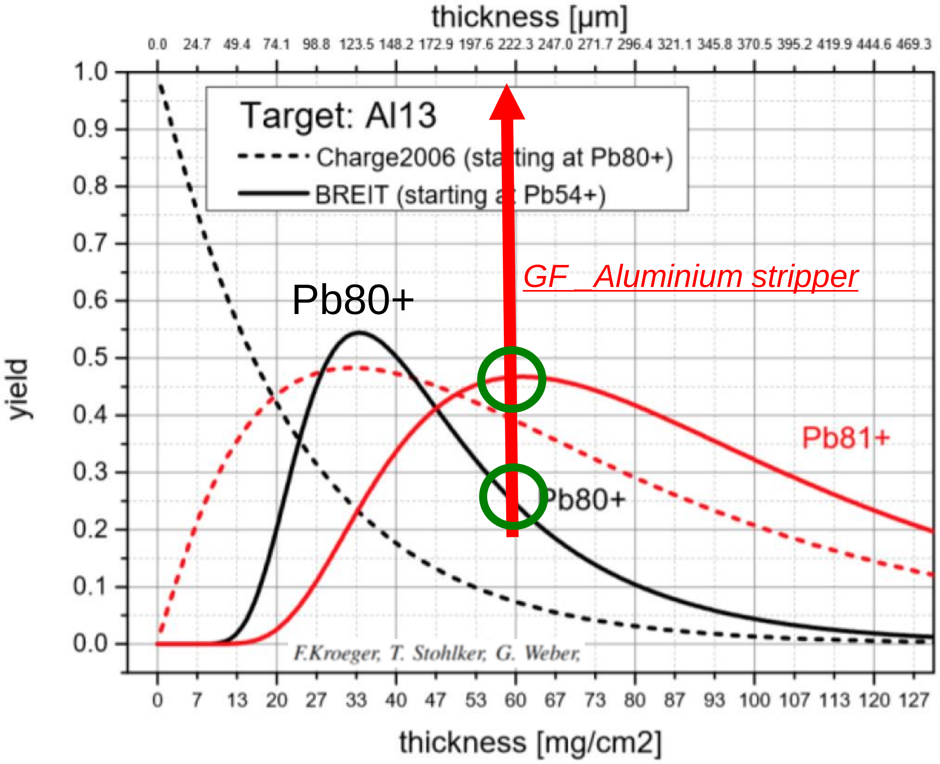
+80,+81,+82

Mean = 193.79 [pixel]
Sigma = 4.80 [pixel]
Amplitude = 82.02 [a.u.]

Mean = 167.50 [pixel]
Sigma = 2.79 [pixel]
Amplitude = 268.32 [a.u.]

Camera Switch: ON   Screen: S1   Filter: filter_1   Video Gain: x 2.2   First Lamp: 0   Second Lamp: 0   Mire: OFF

12:05:27 - Camera TT10.BTV.100123 probably saturated, Saturation Threshold = 3300 Max pixel value = 4095. Reduce Video Gain and use Filters!



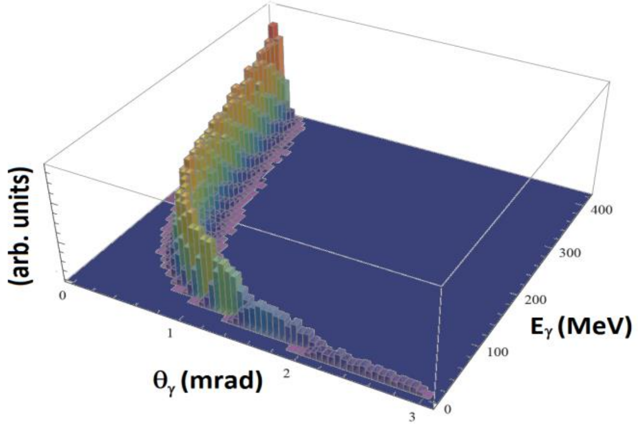
Preliminary BCT measurements suggest:

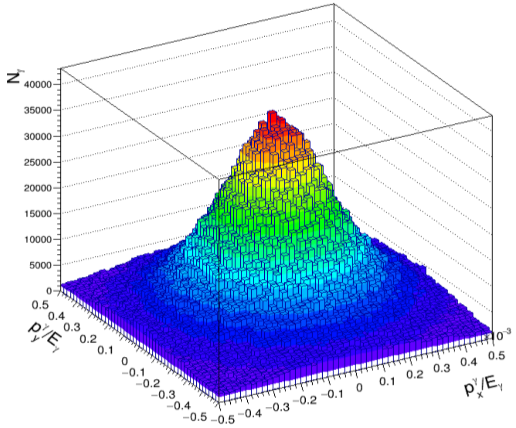
- 30% stripping efficiency for 80+
- 50% stripping efficiency for 81+

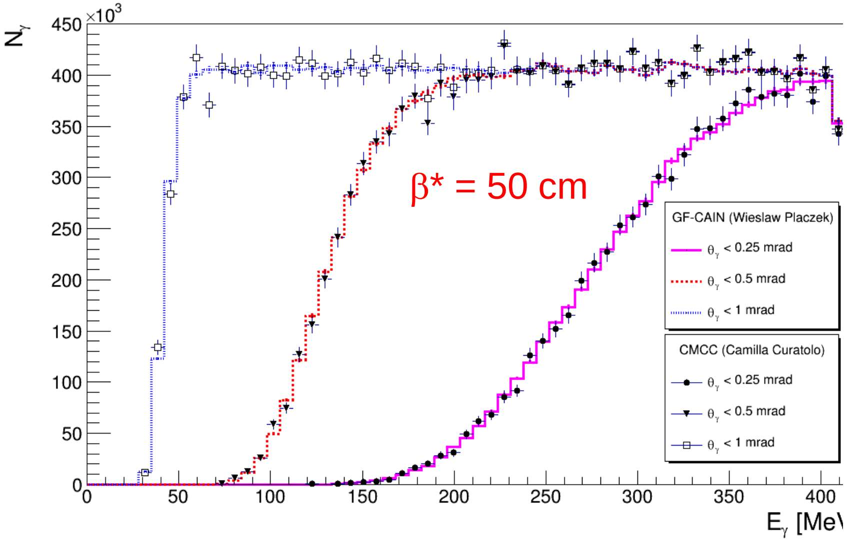
No systematics analysis yet

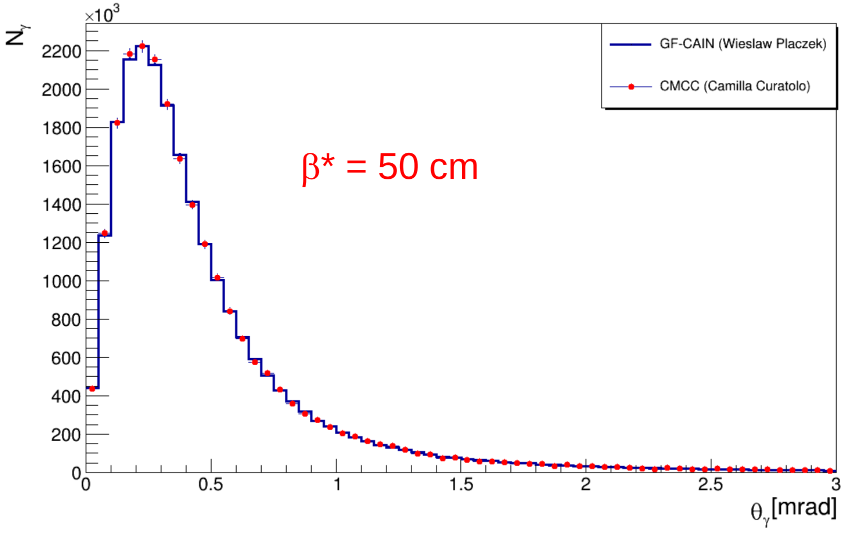
GF software development

Comparisons of two codes: Gamma ray production spectra for +81 Pb beam collisions with laser photons bunches at the top LHC energy

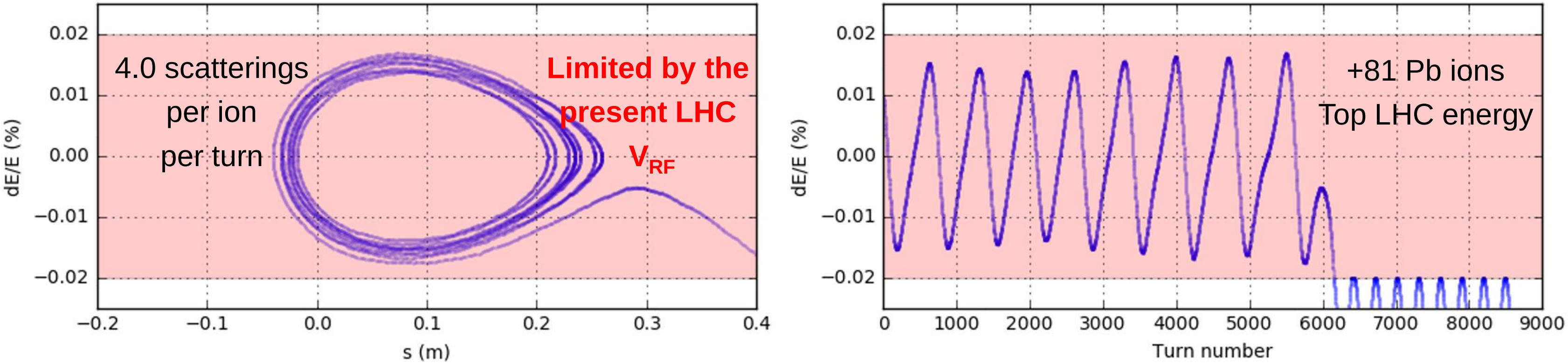








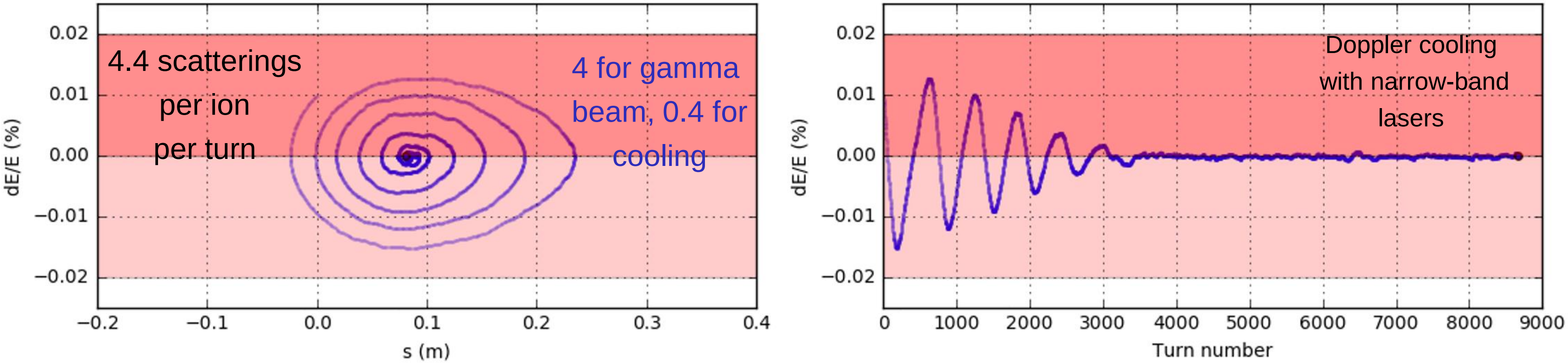
PSI beam stability studies and cooling simulations



4.0 scatterings per ion per turn

Limited by the present LHC V_{RF}

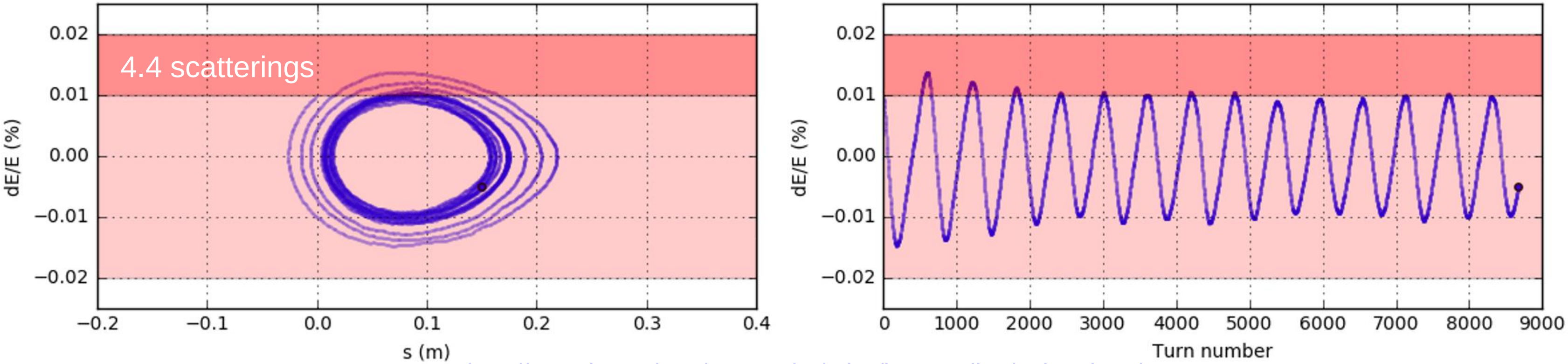
+81 Pb ions
Top LHC energy



4.4 scatterings per ion per turn

4 for gamma beam, 0.4 for cooling

Doppler cooling with narrow-band lasers



4.4 scatterings

http://www.inp.nsk.su/~petrenko/misc/ion_cooling/animations/

Towards the PoP experiment in the SPS

Large number of ion candidates evaluated -- so far two candidates retained…

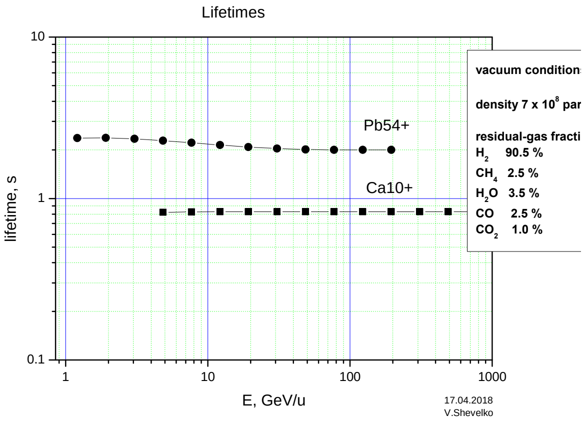
Neon-like Calcium: Ca+10

- ATOMIC GROUND STATE : 1s^2 2s^2 2p^6 $1S_0$
- CHOICE OF EXCITED STATE: 1s^2 2s^2 2p^5 3s $1P_0$
- TRANSITION ENERGY: E = 352.1 eV
- LIFE TIME (excited state) : τ = 6 ps

Sodium-like Lead Pb+71

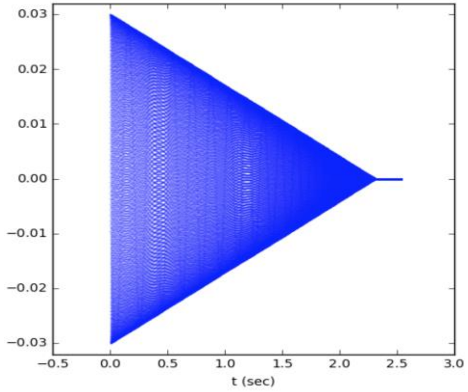
- ATOMIC GROUND STATE : 1s^2 2s^2 2p^6 3s1 $2S_{1/2}$
- CHOICE OF EXCITED STATE: 1s^2 2s^2 2p^5 3p $2P_{1/2}$
- TRANSITION ENERGY: E = 189 eV
- LIFE TIME (excited state): τ = 18 ps

Ca+10 beam life-time in the SPS

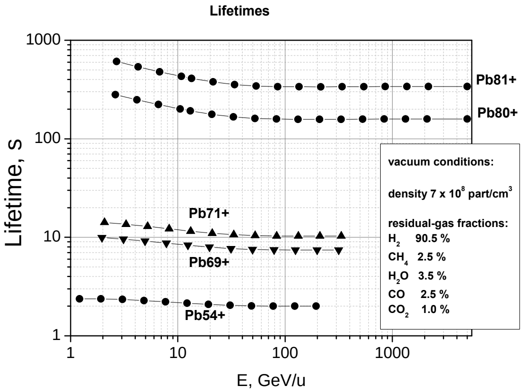


Cooling time in the SPS

(~1 ph absorption/ revolution/ion)

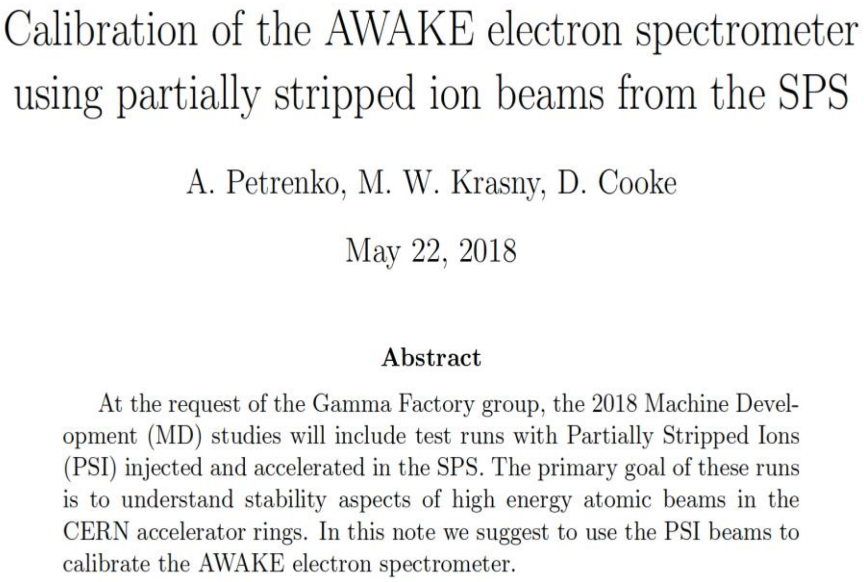


Pb+71 beam life-time in the SPS



Impact/synergy of the GF activities on the on-going and future CERN research programme:

Gamma Factory – AWAKE synergy



Calibration of the AWAKE electron spectrometer using partially stripped ion beams from the SPS

A. Petrenko, M. W. Krasny, D. Cooke

May 22, 2018

Abstract

At the request of the Gamma Factory group, the 2018 Machine Development (MD) studies will include test runs with Partially Stripped Ions (PSI) injected and accelerated in the SPS. The primary goal of these runs is to understand stability aspects of high energy atomic beams in the CERN accelerator rings. In this note we suggest to use the PSI beams to calibrate the AWAKE electron spectrometer.

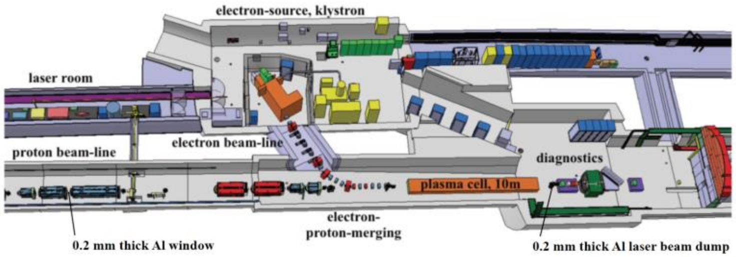
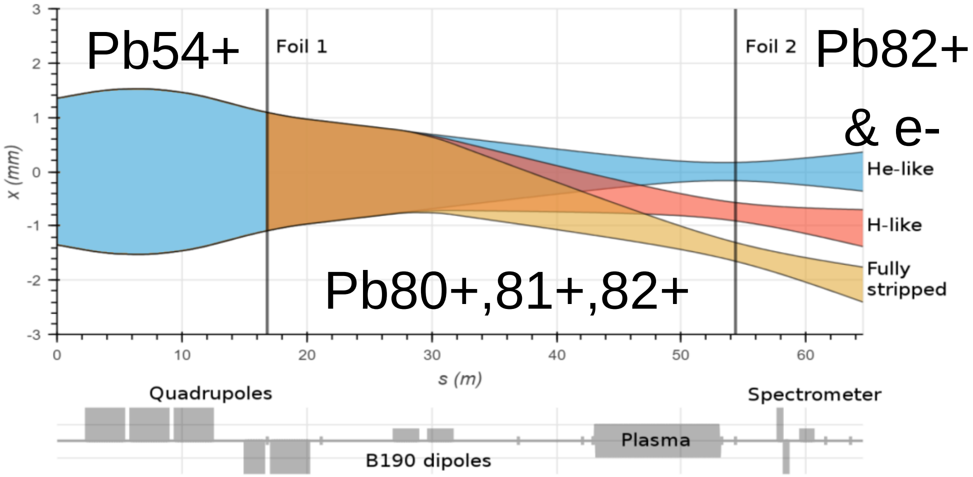
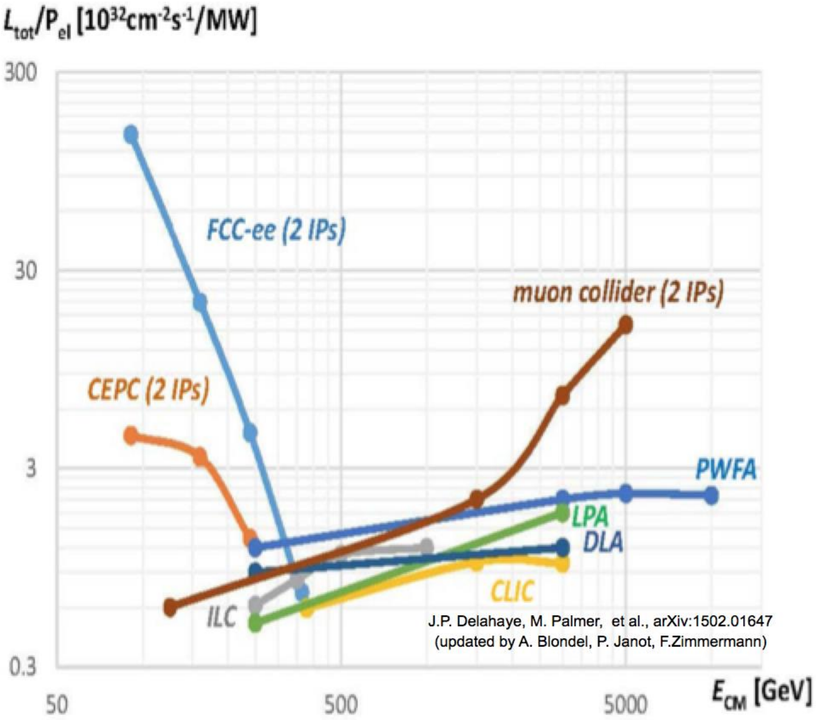


Figure : General layout of the AWAKE experiment. Elec rons will be stripped from th ions at two locations: at the SPS-AWAKE vacuu n window and at the AWAK laser beam dump both of which are made of 0.2 mm thick aluminum foil.



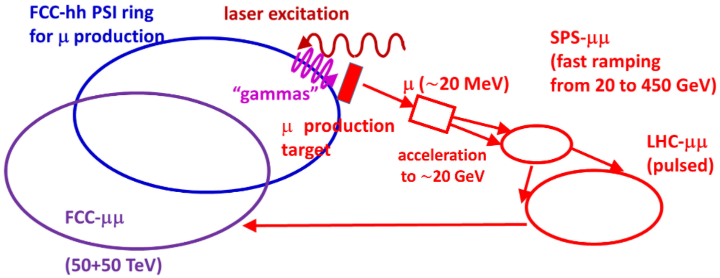
Example: Variants of a multi-TeV scale muon colliders

based on the Gamma Factory concept

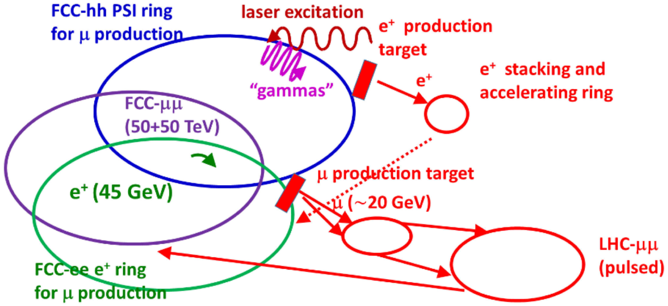


J.P. Delahaye, M. Palmer, et al., arXiv:1502.01647
(updated by A. Blondel, P. Janot, F.Zimmermann)

For the CM-energies above 2 TeV (10 fold increase w.r.t LEP) a muon collider appears to be the only way to achieve a requisite luminosity with reasonable wall power consumption



100 TeV μ collider FCC-μμ with FCC-hh PSI e$^+$
& FCC-ee μ$^\pm$ production



LHC/FCC-BASED MUON COLLIDERS*

F. Zimmermann†, CERN, Geneva, Switzerland

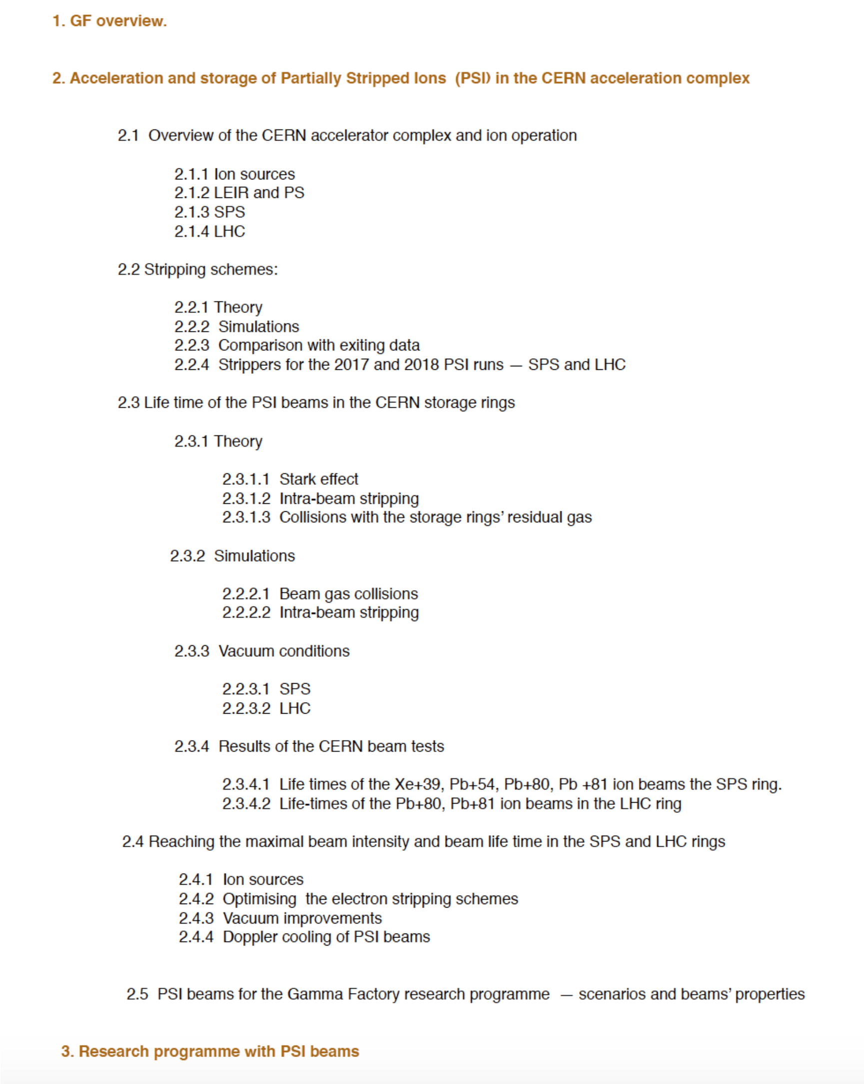
Muon Collider Workshop 2018

1-3 July 2018
Università di Padova - Orto Botanico
Europe/Zurich timezone

The way forward – The GF document for European Strategy Process

Tentative structure of the Gamma Factory group contribution to the PBC document for the European Strategy Update

Initial draft — M.W. Krasny, 21.01.2018



1. GF overview.

2. Acceleration and storage of Partially Stripped Ions (PSI) in the CERN acceleration complex

2.1 Overview of the CERN accelerator complex and ion operation
  2.1.1 Ion sources
  2.1.2 LEIR and PS
  2.1.3 SPS
  2.1.4 LHC

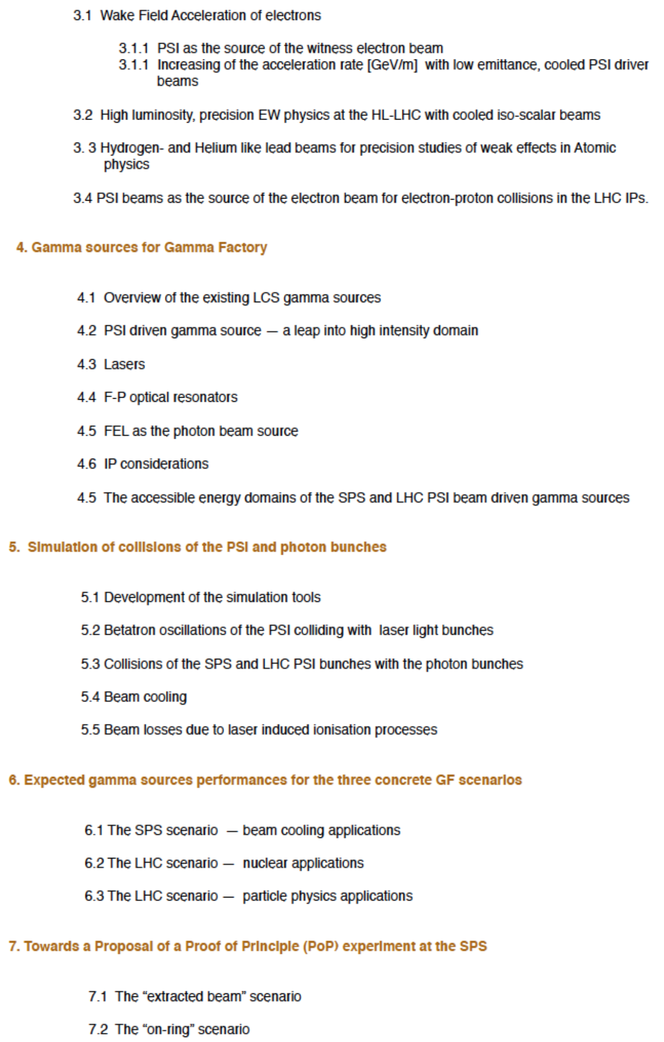
2.2 Stripping schemes:
  2.2.1 Theory
  2.2.2 Simulations
  2.2.3 Comparison with exiting data
  2.2.4 Strippers for the 2017 and 2018 PSI runs — SPS and LHC

2.3 Life time of the PSI beams in the CERN storage rings
  2.3.1 Theory
    2.3.1.1 Stark effect
    2.3.1.2 Intra-beam stripping
    2.3.1.3 Collisions with the storage rings' residual gas
  2.3.2 Simulations
    2.2.2.1 Beam gas collisions
    2.2.2.2 Intra-beam stripping
  2.3.3 Vacuum conditions
    2.2.3.1 SPS
    2.2.3.2 LHC
  2.3.4 Results of the CERN beam tests
    2.3.4.1 Life times of the Xe+39, Pb+54, Pb+80, Pb +81 ion beams the SPS ring.
    2.3.4.2 Life-times of the Pb+80, Pb+81 ion beams in the LHC ring

2.4 Reaching the maximal beam intensity and beam life time in the SPS and LHC rings
  2.4.1 Ion sources
  2.4.2 Optimising the electron stripping schemes
  2.4.3 Vacuum improvements
  2.4.4 Doppler cooling of PSI beams

2.5 PSI beams for the Gamma Factory research programme — scenarios and beams' properties

3. Research programme with PSI beams



3.1 Wake Field Acceleration of electrons
  3.1.1 PSI as the source of the witness electron beam
  3.1.1 Increasing of the acceleration rate [GeV/m] with low emittance, cooled PSI driver beams

3.2 High luminosity, precision EW physics at the HL-LHC with cooled iso-scalar beams

3. 3 Hydrogen- and Helium like lead beams for precision studies of weak effects in Atomic physics

3.4 PSI beams as the source of the electron beam for electron-proton collisions in the LHC IPs.

4. Gamma sources for Gamma Factory

4.1 Overview of the existing LCS gamma sources

4.2 PSI driven gamma source — a leap into high intensity domain

4.3 Lasers

4.4 F-P optical resonators

4.5 FEL as the photon beam source

4.6 IP considerations

4.5 The accessible energy domains of the SPS and LHC PSI beam driven gamma sources

5. Simulation of collisions of the PSI and photon bunches

5.1 Development of the simulation tools

5.2 Betatron oscillations of the PSI colliding with laser light bunches

5.3 Collisions of the SPS and LHC PSI bunches with the photon bunches

5.4 Beam cooling

5.5 Beam losses due to laser induced ionisation processes

6. Expected gamma sources performances for the three concrete GF scenarios

6.1 The SPS scenario — beam cooling applications

6.2 The LHC scenario — nuclear applications

6.3 The LHC scenario — particle physics applications

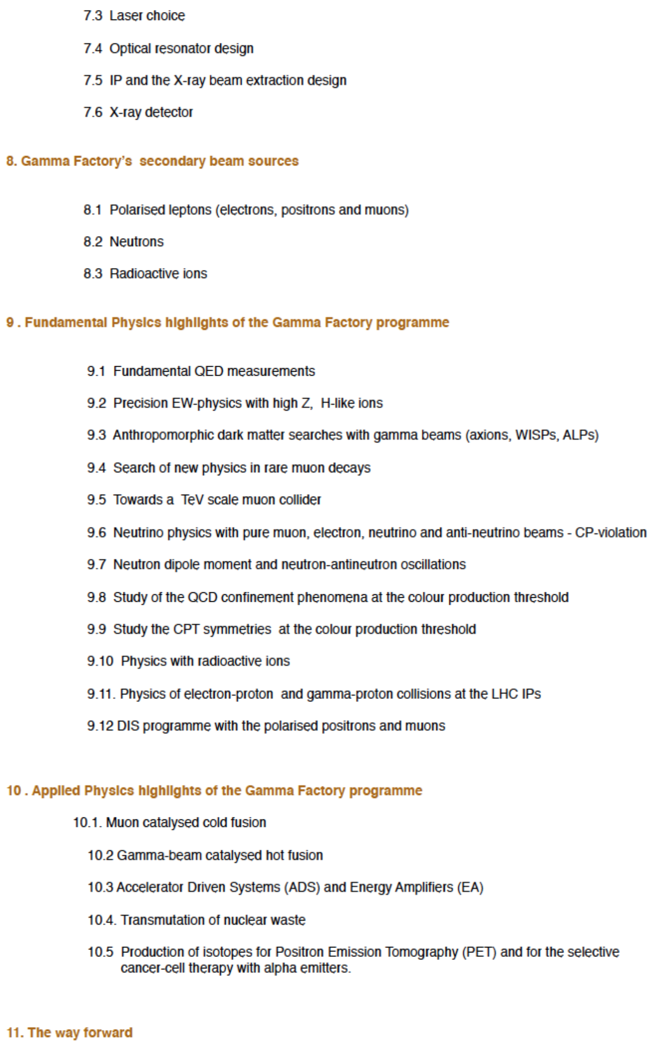
7. Towards a Proposal of a Proof of Principle (PoP) experiment at the SPS

7.1 The "extracted beam" scenario

7.2 The "on-ring" scenario

Tentative structure of the Gamma Factory group contribution to the PBC document for the European Strategy Update

Initial draft — M.W. Krasny, 21.01.2018



7.3 Laser choice

7.4 Optical resonator design

7.5 IP and the X-ray beam extraction design

7.6 X-ray detector

8. Gamma Factory's secondary beam sources

8.1 Polarised leptons (electrons, positrons and muons)

8.2 Neutrons

8.3 Radioactive ions

9 . Fundamental Physics highlights of the Gamma Factory programme

9.1 Fundamental QED measurements

9.2 Precision EW-physics with high Z, H-like ions

9.3 Anthropomorphic dark matter searches with gamma beams (axions, WISPs, ALPs)

9.4 Search of new physics in rare muon decays

9.5 Towards a TeV scale muon collider

9.6 Neutrino physics with pure muon, electron, neutrino and anti-neutrino beams - CP-violation

9.7 Neutron dipole moment and neutron-antineutron oscillations

9.8 Study of the QCD confinement phenomena at the colour production threshold

9.9 Study the CPT symmetries at the colour production threshold

9.10 Physics with radioactive ions

9.11. Physics of electron-proton and gamma-proton collisions at the LHC IPs

9.12 DIS programme with the polarised positrons and muons

10 . Applied Physics highlights of the Gamma Factory programme

10.1. Muon catalysed cold fusion

10.2 Gamma-beam catalysed hot fusion

10.3 Accelerator Driven Systems (ADS) and Energy Amplifiers (EA)

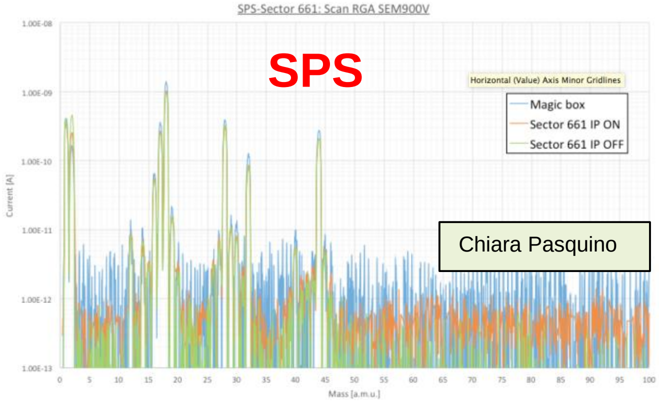
10.4. Transmutation of nuclear waste

10.5 Production of isotopes for Positron Emission Tomography (PET) and for the selective cancer-cell therapy with alpha emitters.

11. The way forward

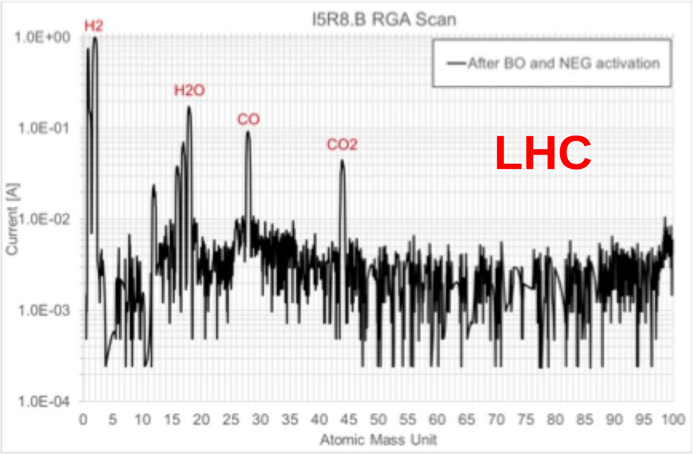
Spares

Residual gas composition: SPS and LHC(warm vacuum chamber)

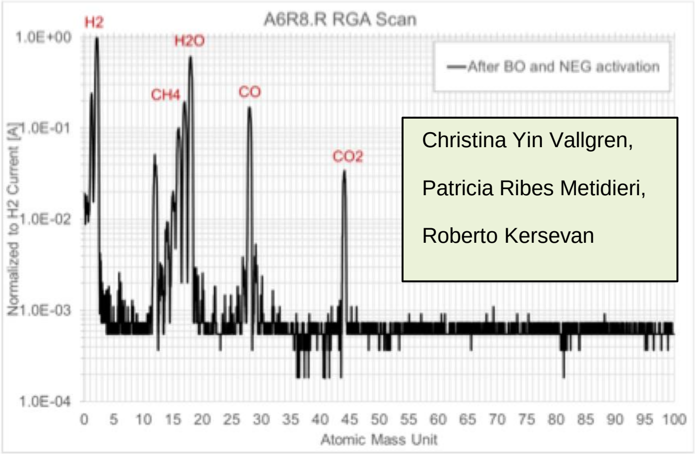


Chiara Pasquino

1. Normalized to the H2 peak.
2. H2 as dominant gas after the bake-out and NEG activation.
3. The main gases in the warm LHC vacuum chamber: H2, CO, CO2, CH4 and H2O.



Interconnects between the MKIs



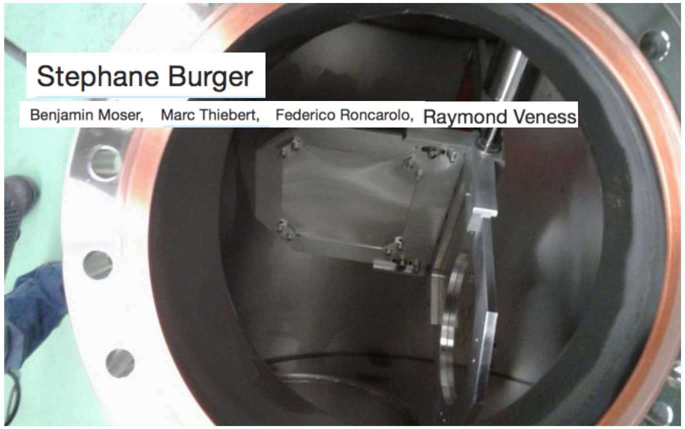
Christina Yin Vallgren,

Patricia Ribes Metidieri,

Roberto Kersevan

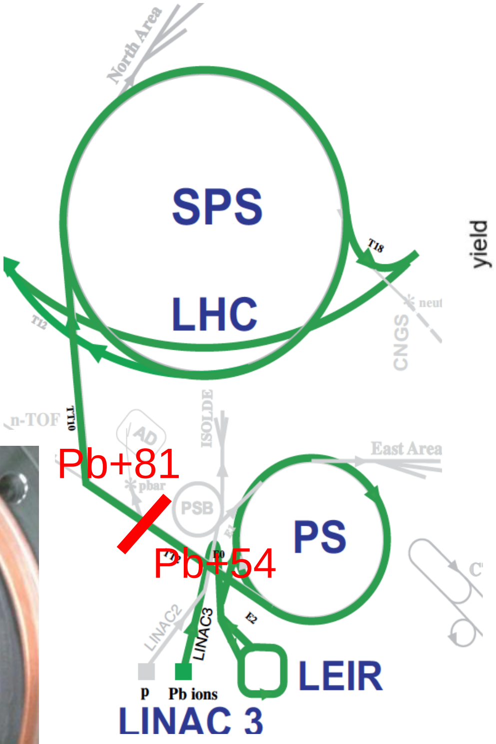
Injection line at Point 8

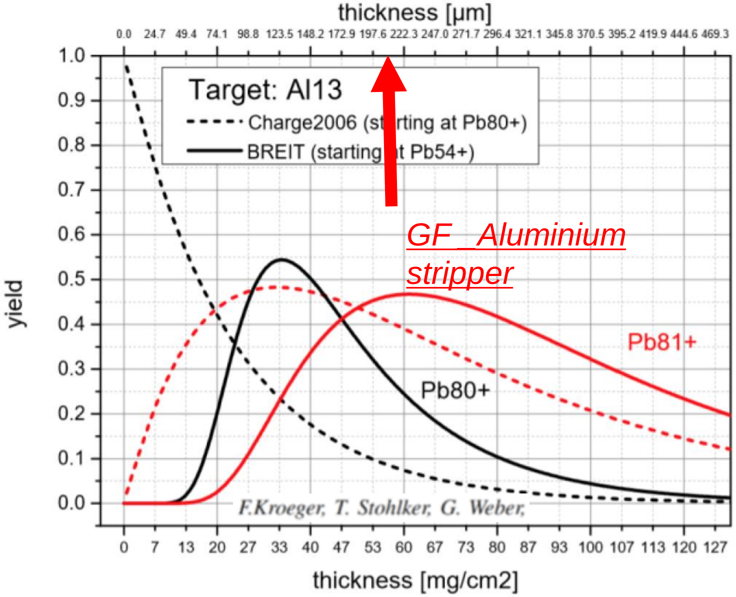
Ion stripping scheme for the 2018 MDs – the “minimal interference” approach: **Pb+81 beam**



Stephane Burger

Benjamin Moser, Marc Thiebert, Federico Roncarolo, Raymond Veness





26.01.2018

The 150μm (212μm crossed by the beam as installed at 45 degrees) thick Al foil has been installed on the FT16.BTV352 in the TT2 line!

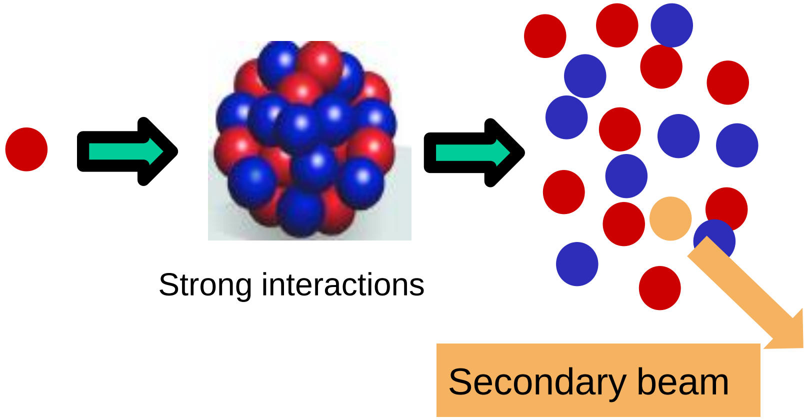
GF research highlights

- ***particle physics*** *(studies of the basic symmetries of the universe, dark matter searches, precision QED studies, rare muon decays, neutrino-factory physics, precision-support measurements for the LHC - DIS physics, muon collider physics)*
- ***nuclear physics*** *(confinement phenomena, link between the quark-gluon and nucleonic degrees of freedom, photo-fission research program)*
- ***accelerator physics*** *(beam cooling techniques, low emittance hadronic beams, plasma wake field acceleration, high intensity polarized positron and muon sources, secondary beams of radioactive ions and neutrons, neutrino-factory)*
- ***atomic physics*** *(electronic and muonic atoms),*
- ***applied physics*** *(accelerator driven energy sources , cold and warm fusion research, isotope production: e.g alpha-emitters for medical applications, …).*

Gamma Factory secondary beams

(from “mining” paradigm to “production” paradigm)

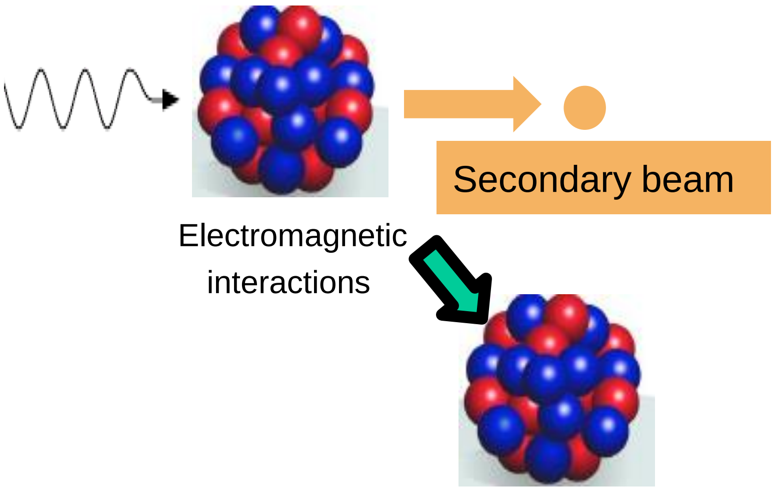
“mining” paradigm:



Strong interactions

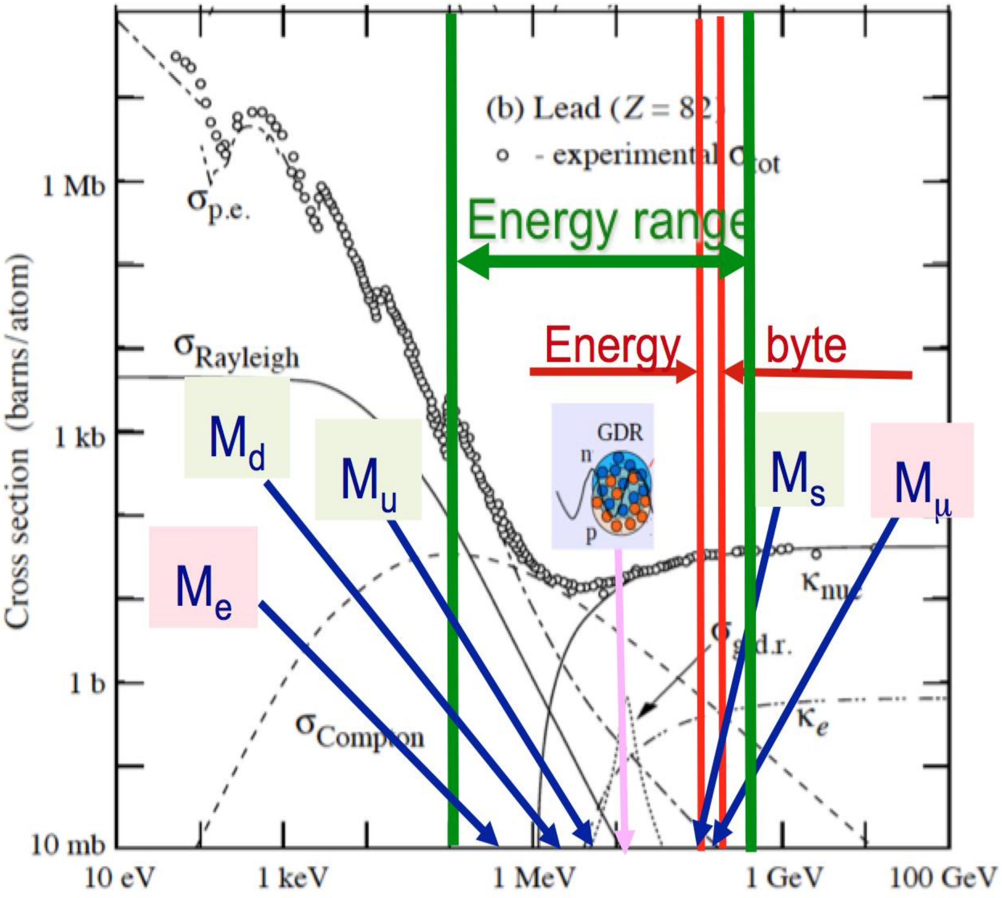
Secondary beam

“production” paradigm:



Secondary beam

Electromagnetic interactions



Uniqueness of CERN

Particle Physics

- basic symmetries
- v-factory physics
- precision QED

dark matter
μ-collider physics
rare μ-decays

Nuclear Physics

- confinement
- quark-gluon and nucleonic degrees of freedom link
- photo-fission

Accelerator Physics

- second. beams of radioact. ions/neutrons
- plasma wake field acceleration
- high-intensity polarized e+ & μ

beam cooling
low emittance hadron beams
v-factory

up p to a factor 10^4 gain in intensity w.r.t to e.g. ALTO

up to a factor 10^3 gain in intensity w.r.t to PSI muon source

up to a factor of 10^4 gain in intensity w.r.t KEK positron source

up to a factor of 10^4 in number of neutrons per 1 kW of the driver beam power

Atomic Physics

- electronic and muonic atoms

Applied Physics

- accelerator driven energy sources
- cold & warm fusion
- isotope production for medical applications

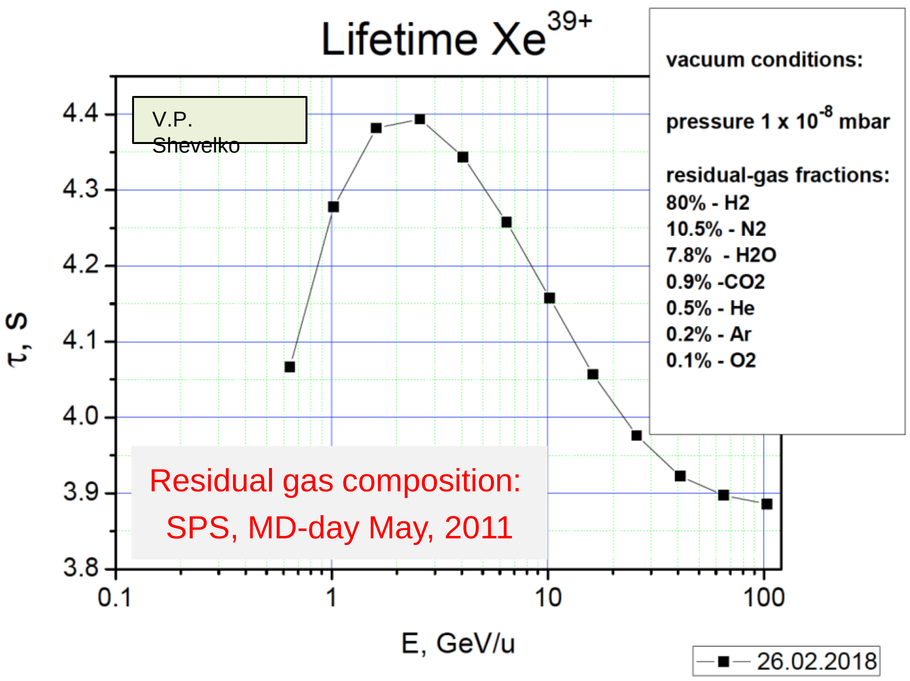
The Gamma Factory beam intensity/quality promise

- ***Highly ionised atoms*** *– new at relativistic energies*
- ***Photons*** *– up to a factor of* 10^7 *gain in intensity w.r.t the present gamma sources*
- ***Polarised positrons*** *– up to a factor of* 10^4 *gain in intensity w.r.t KEK positron source*
- ***Polarised muons*** *- up to a factor* 10^3 *gain in intensity w.r.t to PSI muon source – (low emittance beams → muon collider, neutrino beams)*
- ***Neutrons*** *– up to a factor of* 10^4 *in number of neutrons per 1 kW of the driver beam power*
- ***Radioactive ions*** *– up p to a factor* 10^4 *gain in intensity w.r.t to e.g. ALTO*

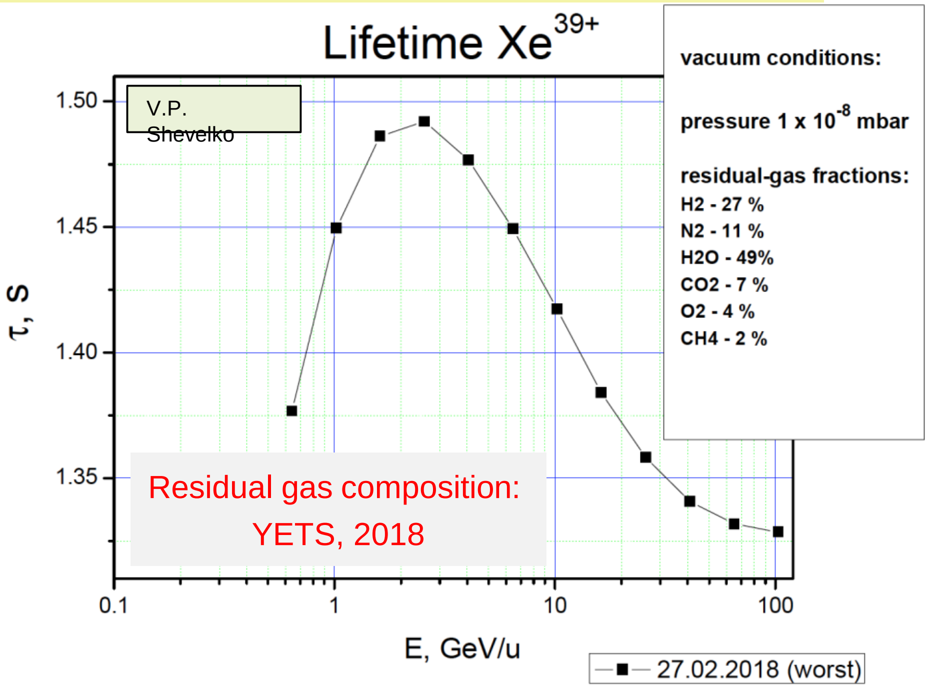
What we have already learned from the 2017 Xe+39 SPS MDs ?

The 2017 SPS measurements allowed us to:

1. Constrain the vacuum quality and the rest gas molecular content.
2. Cross-check the simulation software tools which we use in the extrapolations to other ions species and LHC energies.



Residual gas composition: SPS, MD-day May, 2011



Residual gas composition: YETS, 2018

Residual gas composition: Chiara Pasquino